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Concluding Ms. Henrietta Leavitt's Work on Classical Cepheids in the Magellanic System and other updates of the OGLE Collection of Variable Stars[1]

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ABSTRACT

More than a century ago, Ms. Henrietta Leavitt discovered the first Cepheids in the Magellanic Clouds together with the famous period–luminosity relationship revealed by these stars, which soon after revolutionized our view of the Universe. Over the years, the number of known Cepheids in these galaxies has steadily increased with the breakthrough in the last two decades thanks to the new generation of large-scale long-term sky variability surveys.

Here we present the final upgrade of the OGLE Collection of Cepheids in the Magellanic System which already contained the vast majority of known Cepheids. The updated collection now comprises 9649 classical and 262 anomalous Cepheids. Type-II Cepheids will be updated shortly. Thanks to high completeness of the OGLE survey the sample of classical Cepheids includes virtually all stars of this type in the Magellanic Clouds. Thus, the OGLE survey concludes the work started by Ms. Leavitt.

Additionally, the OGLE sample of RR Lyr stars in the Magellanic System has been updated. It now counts 46 443 variables. A collection of seven anomalous Cepheids in the halo of our Galaxy detected in front of the Magellanic Clouds is also presented.

OGLE photometric data are available to the astronomical community from the OGLE Internet Archive. The time-series photometry of all pulsating stars in the OGLE Collection has been supplemented with new observations.

Key words: *Stars: variables: Cepheids – Stars: variables: RR Lyrae – Magellanic Clouds – Catalogs*

[1] Based on observations obtained with the 1.3-m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution for Science.

1. Introduction

Since the discovery of the first Cepheids in the Magellanic Clouds by Leavitt (1908) and their famous period–luminosity relation (Leavitt and Pickering 1912), the catalogs of variable stars in these galaxies have been steadily growing. Up to the beginning of 1990s, efforts of many observers led to the discovery of about 2500 Cepheids and 300 RR Lyr stars in both Clouds (Artyukhina *et al.* 1995 and references therein). Then, large-scale optical sky surveys, in particular the MACHO (MAssive Compact Halo Object, Alcock *et al.* 1995) and OGLE (Optical Gravitational Lensing Experiment, Udalski *et al.* 2015) projects, increased by a large factor the number of known variable stars in the Magellanic System. The most recent edition of the OGLE Collection of Variable Stars (OCVS) contains 250 anomalous Cepheids (Soszyński *et al.* 2015a), 9535 classical Cepheids (Soszyński *et al.* 2015b), and 45 451 RR Lyr stars (Soszyński *et al.* 2016a) detected in about 650 square degrees covering the Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC), and Magellanic Bridge.

These OGLE samples of pulsating stars have already been used in many studies. For example, for the investigation of the three-dimensional Magellanic System structure (Jacyszyn-Dobrzeniecka *et al.* 2016, 2017, Inno *et al.* 2016), with particular emphasis on the Magellanic Bridge connecting both Magellanic Clouds (Belokurov *et al.* 2017, Wagner-Kaiser and Sarajedini 2017), for constructing metallicity maps of the Magellanic Clouds (Skowron *et al.* 2016), comparing observational and theoretical light curves of Cepheids (Bhardwaj *et al.* 2017, Marconi *et al.* 2017), or detecting peculiar forms of double-periodic pulsations in Cepheids and RR Lyr stars (Smolec *et al.* 2016, Smolec and Śniegowska 2016, Smolec 2017, Soszyński *et al.* 2016b).

The OGLE collections of pulsating stars published so far are practically complete in the central regions of the Magellanic Clouds (about 40 square degrees in the LMC and 14 square degrees in the SMC), because these fields were monitored during the previous phases of the OGLE survey (OGLE-II and OGLE-III) and were independently searched for variable stars. However, external regions of both galaxies have only been observed during the ongoing fourth phase – OGLE-IV. The completeness of the OGLE samples of variable stars identified in these areas has been reduced by technical gaps between CCD detectors of the OGLE mosaic camera. About 7% of stars fell into these gaps which decreased the completeness of our collection by the same factor.

In this paper we supplement the OGLE Collection of Cepheids and RR Lyr stars in the Magellanic Clouds with objects detected in these regions. The updated collection now contains practically all classical Cepheids. Thus, with the update presented here we conclude the work on classical Cepheids started by Ms. Leavitt. The upgraded OCVS also contains the vast majority of RR Lyr stars and anomalous Cepheids in the Magellanic System covered by the OGLE-IV fields.

The paper is organized as follows. Section 2 presents the dataset used in this investigation. In Section 3 we briefly describe how pulsating stars were selected. The upgraded collection of Cepheids and RR Lyr stars in the Magellanic Clouds is presented in Section 4, while a sample of anomalous Cepheids belonging to our Galaxy is discussed in Section 5. Section 6 is dedicated to the completeness estimation and comparison with the results from other large-scale sky surveys. The paper is concluded in Section 7.

2. Observations and Data Reduction

The observational data used in this study come from the auxiliary photometric databases of the OGLE-IV project and were obtained from 2010 to 2016 with the 1.3-meter Warsaw Telescope at Las Campanas Observatory, Chile. The observatory is operated by the Carnegie Institution for Science. The Warsaw Telescope is equipped with a 256 Megapixel mosaic camera composed of 32 CCD detectors (Udalski *et al.* 2015). The standard high precision OGLE photometry of the Magellanic System fields was obtained with the OGLE data pipeline (Udalski 2003, Udalski *et al.* 2015) based on the Difference Image Analysis (DIA) method (Alard and Lupton 1998, Woźniak 2000).

The OGLE-IV camera has several technical gaps between the detectors, which results in strips of "dead zones" in the sky, *i.e.*, regions inaccessible during a single exposure. The strips are from $17''$ to $97''$ wide which decreases the completeness of the regular OGLE-IV databases by about 7%. To minimize this problem, a dithering technique was applied to the OGLE-IV observations during two observing seasons. Additionally, a natural dithering caused by imperfections in the telescope pointing ($rms \approx 15''$) systematically filled the gaps between the CCD detectors. One should, however, remember that the typical number of observations secured in these regions is significantly smaller than in the remaining parts of the fields.

The OGLE-IV collection of images is so large that it is now possible to create deep, good-seeing reference images filling practically the entire area covered by the mosaic camera. Therefore we decided to repeat the DIA reductions focusing on the regions that were not covered by the standard OGLE-IV reductions before.

The new DIA reference images for each OGLE-IV field in the Magellanic System were constructed from 50–100 best individual I-band images, which resulted in much deeper photometry than in the regular reference images composed typically of up to ten images. Our deep reference images filled practically all "dead zones". The photometry of stars in these regions was obtained using the standard OGLE pipeline (Udalski 2003) running with this new set of deep reference images. We extracted photometry for all objects detected in the "dead zones" and their surroundings (for testing purposes). Additionally, we obtained time-series photometry of all bright stars ($I < 15$ mag) regardless of their position on the detector. Some of these objects could have been saturated on the regular OGLE reference images (which typically had better seeing) so their photometry in the standard databases was not available. Now, with the new reductions some of them could be measured.

The new auxiliary *I*-band OGLE databases of the Magellanic System fields were created based on the new reductions. Because the new deep reference images share the same flux scale as the standard ones, the auxiliary databases are in the same photometric system as the standard OGLE databases. The calibrations to the standard system were then carried out in the identical way as for the standard databases (Udalski *et al.* 2015).

The total area covered by the extended OGLE-IV fields in the Magellanic System reaches 670 square degrees. The number of data points in the new auxiliary photometric database depends mainly on the position of a star in the field. For the sample of the newly detected Cepheids and RR Lyr stars the median number of the *I*-band observations is 70, but for individual stars we obtained from 13 to more than 600 data points.

Because the new reductions were carried out only for the *I*-band images (for variability search), the *V*-band light curves come from the standard DIA reductions, and about half of the newly detected variables do not have the *V*-band measurements. For the remaining stars, the median number of the *V*-band data points is seven, but in some cases it exceeds 100.

3. Selection of Cepheids and RR Lyr Stars

The new auxiliary OGLE databases were searched for variable stars. The procedure was in principle the same as that described by Soszyński *et al.* (2015a, 2016a), but we took special care to ensure the high completeness of the variability detection in poorly sampled light curves. All stars with more than ten *I*-band data points were searched for periodicity using two different methods: the discrete Fourier transform implemented in the FNPEAKS code[2] and the Analysis of Variance algorithm. Our procedures were applied to about 18 million light curves.

From this sample we visually inspected the light curves with the highest signal-to-noise ratio and periods from 0.2 d to 50 d. We paid special attention to stars located in the Cepheid instability strip in the color–magnitude diagram ($0.3 < V-I < 1.1$ mag), lying within a wide strip in the period–luminosity diagram covering all types of Cepheids and RR Lyr stars, and with *I*-band amplitudes larger than 0.1 mag. Based on the light curve morphology, we selected candidates for pulsating stars, eclipsing binaries, and other variable stars. Then, an analysis of periods, mean luminosities, colors, Fourier parameters of the light curves, and period ratios (in multiperiodic variables) allowed us to divide our sample of pulsating stars into classical, type II, anomalous Cepheids, and RR Lyr stars. Finally, objects in each group were divided into subtypes, according to their pulsation modes. For completeness, we supplemented our list by several well-known long-period classical Cepheids that are too bright to be monitored by OGLE.

[2]http://helas.astro.uni.wroc.pl/deliverables.php?lang=en&active=fnpeaks

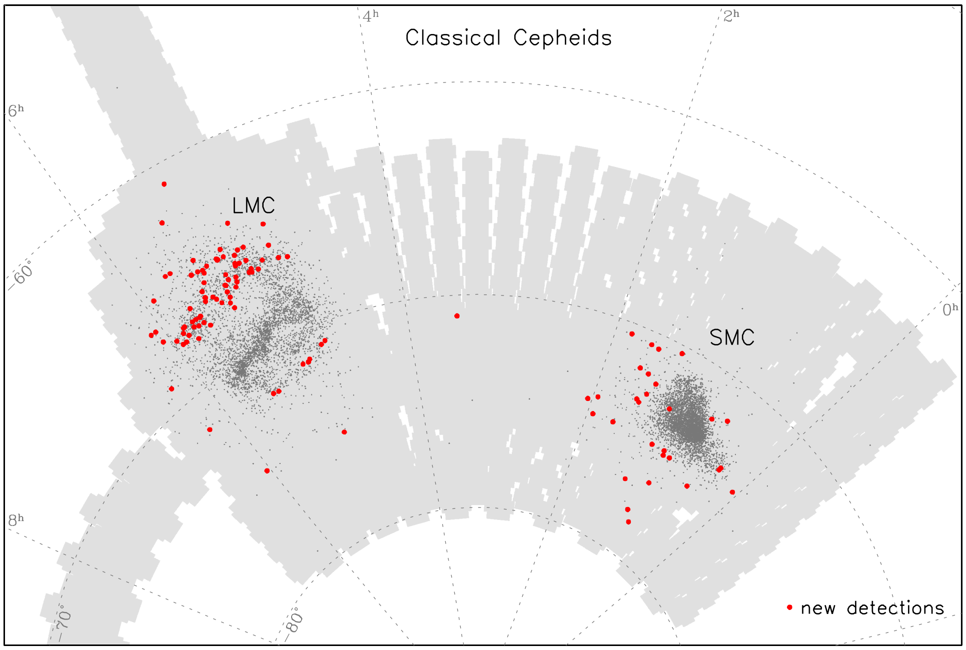

Fig. 1. Spatial distribution of classical Cepheids in the Magellanic System. Dark gray points mark objects included in the previous edition of the OCVS, while red points indicate newly detected Cepheids. The gray area shows the sky coverage of the OGLE-IV fields.

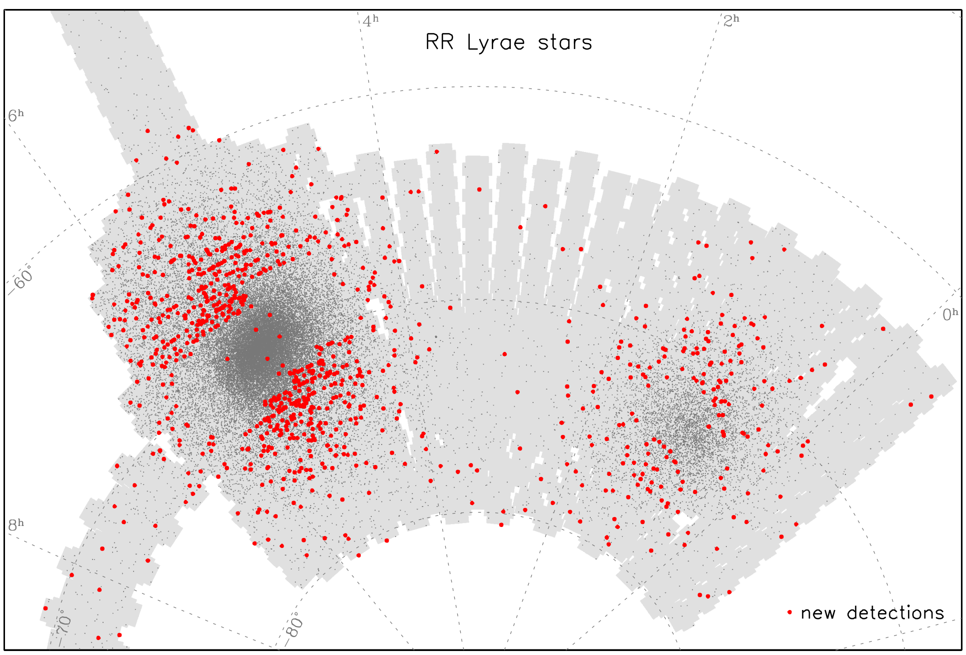

Fig. 2. Spatial distribution of RR Lyr stars toward the Magellanic System. Dark gray points mark variables included in the previous edition of the OCVS, while red points indicate newly detected stars. The gray area shows the OGLE-IV footprint.

Our search led to the identification of 115 classical Cepheids, 994 RR Lyr stars, and 12 anomalous Cepheids that were not included in the OCVS, so far. Red points in Figs. 1–3 show the positions of these stars in the sky. As expected, almost all new Cepheids and the vast majority of RR Lyr variables are located outside the OGLE-III fields. It is worth noting that one of the newly detected classical Cepheids (OGLE-SMC-CEP-4987) lies in the region of the Magellanic Bridge, a stream of neutral gas and stars that links the two Clouds. It increases the sample of the Bridge Cepheids to ten. Cepheids in the Magellanic Bridge were recently analyzed by Jacyszyn-Dobrzeniecka *et al.* (2016).

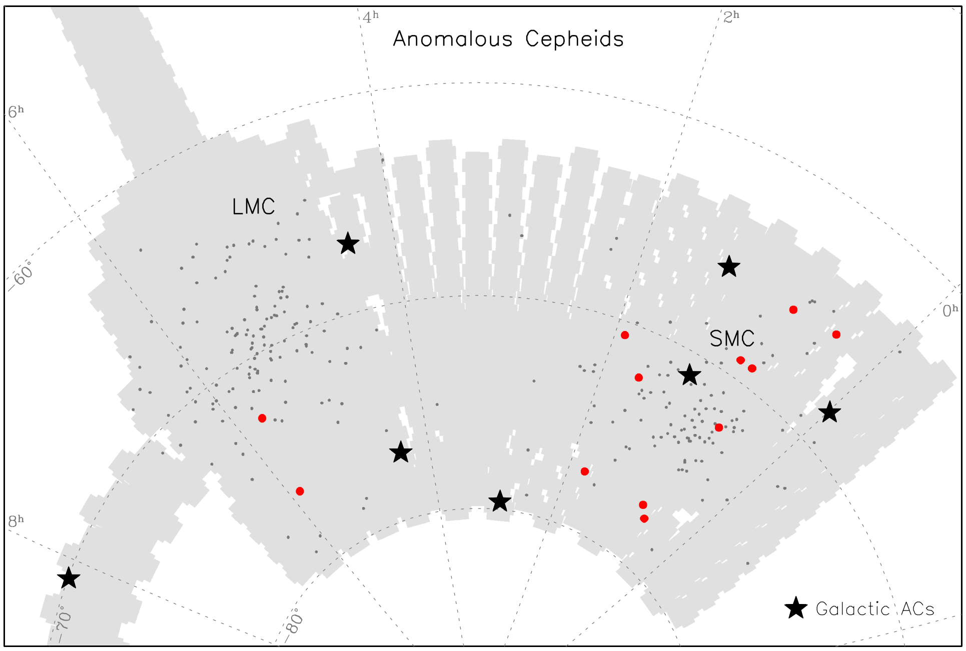

Fig. 3. Spatial distribution of anomalous Cepheids in the Magellanic System. Dark gray points mark variables included in the previous edition of the OCVS, red points indicate newly detected objects, and star symbols show Galactic anomalous Cepheids in the foreground of the Magellanic Clouds. The gray area shows the sky coverage of the OGLE-IV fields.

4. OGLE Collection of Cepheids and RR Lyr Stars in the Magellanic Clouds

The newly detected Cepheids and RR Lyr stars have been added to the OCVS (Soszyński *et al.* 2015ab, 2016a). The full collection contains now 9 649 classical Cepheids, 262 anomalous Cepheids, and 46 443 RR Lyr variables in the Magellanic System. The exact numbers of stars pulsating in various modes in both Clouds are summarized in Table 1. The collection of type II Cepheids in the Magellanic Clouds will be published elsewhere.

T a b l e 1

Numbers of Pulsating Stars in the Magellanic Clouds

Type	Subtype	LMC	SMC	Total
Classical Cepheids	all	4 704	4 945	9 649
	F	2 476	2 753	5 229
	1O	1 775	1 793	3 568
	2O	26	91	117
	F/1O	95	68	163
	1O/2O	322	239	561
	1O/3O	1	0	1
	2O/3O	1	0	1
	F/1O/2O	1	0	1
	1O/2O/3O	7	1	8
Anomalous Cepheids	all	143	119	262
	F	102	78	180
	1O	41	41	82
RR Lyrae Stars	all	39 871	6 572	46 443
	RRab	28 193	5 105	33 298
	RRc	9 663	801	10 464
	RRd	1 995	663	2 658
	anom. RRd	20	3	23

The entire collection is available *via* anonymous FTP site:

ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/

At this site, we provide basic parameters of each object: classification, J2000 equatorial coordinates, pulsation periods (derived with the TATRY code by Schwarzenberg-Czerny 1996), *I*- and *V*-band mean magnitudes, amplitudes, epochs of maximum light, Fourier coefficients, and time series: *I*- and *V*-band photometry obtained from 2010 to mid-2016 during the OGLE-IV project (earlier OGLE observations for some stars are available in the OGLE-III Catalog of Variable Stars). The light curves of pulsating stars released by Soszyński *et al.* (2015ab, 2016a) have been supplemented with new observations collected by the end of July 2016. Furthermore, we provide, for the first time, the OGLE-IV photometry for about 2500 Cepheids and RR Lyr variables known from the previous phases of the OGLE survey (OGLE-II and OGLE-III), but located in the gaps between the CCD chips of the OGLE-IV camera.

A few objects have been reclassified in this edition of the OCVS. A short-period pulsator OGLE-LMC-CEP-1154 has been moved from the list of classical Cepheids to the list of RR Lyr stars (the regular OGLE light curve of this star was affected by blending). Two stars previously classified as RR Lyr variables (OGLE-LMC-RRLYR-03358, OGLE-LMC-RRLYR-16235) are likely eclipsing binaries.

We removed these stars from the collection. In several other RR Lyr stars we corrected their pulsation periods, which in one case (OGLE-LMC-RRLYR-21326) led to a modification of the pulsating mode.

5. Galactic Anomalous Cepheids

Until recently, only one anomalous Cepheid was known in the field of our Galaxy: a first-overtone pulsator XZ Ceti (Szabados *et al.* 2007). However, thanks to a large number of anomalous Cepheids discovered by the OGLE survey in the Magellanic Clouds (Soszyński *et al.* 2015a) we demonstrated that coefficients ϕ_{21} and ϕ_{31} derived from the Fourier light curve decomposition are useful discriminants between various types of Cepheids and RR Lyr stars. Using the Fourier analysis, Soszyński *et al.* (2015a) discovered four Galactic anomalous Cepheids in the foreground of the Magellanic Clouds – the first fundamental-mode anomalous Cepheids known in the Milky Way halo.

Table 2

Galactic Anomalous Cepheids in the Foreground of the Magellanic Clouds

Identifier	Pulsation mode	P [d]	$\langle I\rangle$ [mag]	$\langle V\rangle$ [mag]	R.A. [J2000.0]	Dec. [J2000.0]
OGLE-GAL-ACEP-001	F	1.3204588	14.405	14.904	$23^h59^m14\overset{s}{.}51$	$-68°13'56\overset{''}{.}6$
OGLE-GAL-ACEP-002	F	0.8337190	16.824	17.376	$01^h10^m57\overset{s}{.}51$	$-71°01'57\overset{''}{.}6$
OGLE-GAL-ACEP-003	F	1.0701226	14.927	15.445	$01^h20^m14\overset{s}{.}74$	$-65°42'38\overset{''}{.}3$
OGLE-GAL-ACEP-004	F	0.7978865	15.520	16.185	$02^h56^m08\overset{s}{.}54$	$-79°38'08\overset{''}{.}5$
OGLE-GAL-ACEP-005	1O	0.5041628	15.719	16.159	$04^h22^m11\overset{s}{.}04$	$-66°48'08\overset{''}{.}7$
OGLE-GAL-ACEP-006	F	1.8836187	12.461	13.014	$04^h23^m51\overset{s}{.}47$	$-76°54'42\overset{''}{.}8$
OGLE-GAL-ACEP-007	1O	0.5201967	15.138	15.933	$08^h10^m34\overset{s}{.}29$	$-70°02'34\overset{''}{.}8$

In this study, we extend our sample of Galactic anomalous Cepheids to seven: five fundamental-mode and two first-overtone pulsators. All these stars have light curve shapes typical for anomalous Cepheids, but they are much brighter than their counterparts in the Magellanic System. Thus, we assume that they are Galactic variables. Table 2 gives their basic properties, while Fig. 3 shows their positions in the sky.

Note that the OCVS also includes Galactic RR Lyr stars located in the foreground of the Magellanic Clouds. However, it is impossible to completely separate RR Lyr stars belonging to the Milky Way, LMC, and SMC, because halos of these three galaxies overlap with each other. For this reason the Galactic RR Lyr stars have designations which follow the scheme for Magellanic Cloud variables (OGLE-LMC-RRLYR-NNNNNN or OGLE-SMC-RRLYR-NNNNNN).

For anomalous Cepheids the situation is different – for our seven objects there is no doubt that all of them are members of the Milky Way. Therefore we propose a new designation for Galactic anomalous Cepheids: OGLE-GAL-ACEP-NNN, where NNN is a three-digit consecutive number. Their *I*- and *V*-band OGLE light curves can be downloaded from the FTP site

ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/gal/acep/

Our investigation shows that anomalous Cepheids must be quite numerous in the Milky Way halo. We found on average one Galactic anomalous Cepheid per 100 square degrees of the sky, so simple scaling to the whole sphere gives more than 400 such pulsators in our Galaxy. We expect that a number of anomalous Cepheids will be identified in the OGLE fields in the Galactic bulge and disk.

6. Completeness of the Sample

Soszyński *et al.* (2015b, 2016a) estimated that the completeness of the OCVS in the central regions of the Magellanic Clouds, which were intensively monitored during the OGLE-II and OGLE-III projects, is nearly 100%, because these regions were independently searched for variable stars at least three times. In turn, our samples in the outer fields were affected by the gaps between CCD detectors of the mosaic camera, which effectively reduced the completeness by about 7%. The main goal of this investigation was to fill these gaps.

Our new sample of 115 classical Cepheids increases by 6.9% the total sample of Cepheids in the outer regions of the Magellanic Clouds (outside the OGLE-III fields). This is virtually equal to the expected 7% of the missed objects in the previous edition of the OCVS. Moreover, the OGLE-IV fields seem to cover the entire area where classical Cepheids in the Magellanic System are present, thus we are convinced that the OGLE Collection of Classical Cepheids in the Magellanic System is now practically complete. Thus, with this final update of the OCVS we conclude the work started by Ms. Henrietta Leavitt (1908) over a century ago.

Of course, it is still possible that a few additional classical Cepheids can be hidden in the far outskirts of the Magellanic Clouds, outside the OGLE fields. We could also miss some objects located very close to bright stars overexposed on the OGLE reference images and masked around during the photometric reduction processes (*e.g.*, Udalski *et al.* 2016). Other Cepheids that can be overlooked are pulsators with unusual behavior, for example single-mode second-overtone Cepheids which show very small amplitudes and sinusoidal light curves. Nevertheless, the number of such objects is certainly negligible.

In turn, the new sample of RR Lyr stars enlarges the OGLE collection of these variables in the outer fields by 5.5%. It is more difficult to detect RR Lyr variables than Cepheids, because they are fainter and many of them show the Blazhko effect which adds noise to the phased light curves. Therefore the completeness of RR Lyr stars must be lower, but it is still above 95%. Obviously, this value refers to the area of the sky covered by the OGLE fields. As one can see in Fig. 2, the old stellar population in the Magellanic System extends in every direction from the LMC and SMC centers and reaches regions beyond the OGLE-IV sky coverage. The same remark applies to anomalous Cepheids, which show similar spatial distribution to RR Lyr stars (Soszyński *et al.* 2015a).

We cross-matched our updated collection with recently published lists of pulsating stars in the Magellanic Clouds. Kim *et al.* (2014) identified 4 212 candidates for Cepheids of various types and 26 855 candidates for RR Lyr stars in the light curve database collected by the EROS-2 microlensing survey. Our sample includes in total 26 685 Cepheids and RR Lyr objects from these lists, although in some cases our detailed classification does not match the Kim's *et al.* (2014) suggestions. The remaining over 4000 candidates for classical pulsating stars published by Kim *et al.* (2014) seem to be variable stars of other types.

The OGLE extended photometric database contains *I*-band light curves of 298 out of 299 candidates for Cepheids in the SMC detected by Moretti *et al.* (2016) based on the near-infrared VMC survey. We confirm that 39 of these stars are real classical Cepheids and two objects are anomalous Cepheids. Most of the remaining 257 VMC candidates for Cepheids are constant or nearly constant stars.

The sample of 599 classical, anomalous and type II Cepheids and 2595 RR Lyr stars identified by the Gaia Consortium in the outskirts of the LMC (Clementini *et al.* 2016) was discussed in detail by Udalski *et al.* (2016). The current version of the OCVS contains 2845 out of 3194 Gaia candidates for Cepheids and RR Lyr stars, although in several cases our classification differs from that proposed by Clementini *et al.* (2016). For example three Gaia Cepheids are re-classified as RR Lyr variables. The missing objects were also analyzed by Udalski *et al.* (2016) – most of them lie outside the OGLE-IV fields, but the Gaia sample includes also a few dozen misclassified objects.

7. Summary

We presented here an updated version of the OGLE Collection of Cepheids and RR Lyr Stars in the Magellanic System. A collective effort of many astronomers started by Ms. Henrietta Leavitt (1908) finally led to the discovery of practically all classical Cepheids in the Magellanic System and of the vast majority of other types of classical pulsating stars. The OCVS offers high-quality, long-term light curves obtained in the standard *I*- and *V*-band filters, well suited for studying properties of pulsating stars and their host galaxies.

Studies of exotic pulsation modes, period changes, phase and amplitude modulations, mode switching, mapping of the three-dimensional distribution of the young and old stellar population in the Magellanic System, exploring the star formation history and past interactions between the Clouds and Milky Way, mapping of the interstellar extinction, calibration of the period–luminosity relations, tracing metallicity gradients are another examples of investigations that can be conducted with the OGLE sample of Cepheids and RR Lyr stars.

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